LLNL-TR-678615

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Highly Sensitive Electro-Optic Modulators

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October 26, 2015

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Peter DeVore (15-FS-011)

Abstract

There are very important diagnostic and communication applications that receive faint electrical signals to be transmitted over long distances for capture. Optical links reduce bandwidth and distance restrictions of metal transmission lines; however, such signals are only weakly imprinted onto the optical carrier, resulting in low fidelity transmission. Increasing signal fidelity often necessitates insertion of radio-frequency (RF) amplifiers before the electro-optic modulator, but (especially at high frequencies) RF amplification results in large irreversible distortions. We have investigated the feasibility of a Sensitive and Linear Modulation by Optical Nonlinearity (SALMON) modulator to supersede RF-amplified modulators. SALMON uses cross-phase modulation, a manifestation of the Kerr effect, to enhance the modulation depth of an RF-modulated optical wave. This ultrafast process has the potential to result in less irreversible distortions as compared to a RF-amplified modulator due to the broadband nature of the Kerr effect. Here, we prove that a SALMON modulator is a feasible alternative to an RF-amplified modulator, by demonstrating a sensitivity enhancement factor greater than 20 and significantly reduced distortion.

Background and Research Objectives

Many diagnostic and communication systems, such as cellular telephone networks and radar, receive weak signals that must be amplified and remotely sent over long distances to receivers. Although optical links alleviate the bandwidth and distance restrictions of metal wires for transmission to receivers, weak signals are unable to fully modulate an optical wave, resulting in poor dynamic range. Radio-frequency (RF) amplifiers are commonly employed before electro-optic modulators, resulting in RF-amplified modulators, to increase modulation for fiber optic delivery, but severely degrade fidelity.

We have investigated the feasibility of a Sensitive and Linear Modulation by Optical Nonlinearity (SALMON) modulator to supersede radio-frequency-

(RF-)amplified modulators. SALMON uses the Kerr effect, which is a change in a material's refraction in response to an applied optical field, to increase modulation depth in the optical domain with less irreversible distortion than use of a RF amplifier in the electrical domain. An electro-optic modulator combined with a SALMON stage to increase sensitivity after electro-optic modulation is a SALMON modulator. The prototypical SALMON modulator uses the cross-phase modulation aspect of the Kerr effect to perform modulation depth enhancement. Cross-phase modulation is where one wavelength of light can affect the phase of another wavelength, proportional to the first wavelength's instantaneous power. This has the potential to eliminate the RF amplifier by enhancing the modulation depth of a pre-existing modulator by exploiting the multiplicative power dependence of cross-phase modulation. In addition, as cross-phase modulation is an ultrafast process, its modulation frequency dependence should be drastically reduced, resulting in less irreversible distortions in a SALMON modulator as compared to a RF-amplified modulator. Our goal was to address how much sensitivity enhancement can be achieved (at least 10 times), the feasibility that a SALMON modulator results in less-irreversible distortion, and the noise and distortion impact. Results described below prove the feasibility of such an approach.

Scientific Approach and Accomplishments

We have found that the SALMON modulator can achieve sensitivity enhancements greater than 20 times while exhibiting less irreversible distortion, and we have also investigated its impact on noise. For this study, we experimentally quantified the sensitivity enhancement, distortion and noise of a conventional modulator and our SALMON modulator with an experimental test bed. We also created a physics-based end-to-end model to evaluate and optimize experiments.

Before going over the experimental results, it is helpful to describe the results of our modeling effort. We first show the relationship between voltage into an electro-optic modulator and voltage out of the photodetector for a general optical link, which we calculated using expressions from Chang (2002). When an electro-optic modulator is fed by a carrier laser and input RF voltage $V_{RF,in}$ [V] and subsequently photodetected, the output voltage $V_{RF,out}$ [V] is related to system parameters by

$$V_{RF,out} = V_{RF,in}\left(\pi P_{car} R_L R_{esp}/(4V_\pi)\right) \text{ Eq. 1}$$

where P_{car} [W] is the carrier laser power, R_L [Ω] is the photodetector load resistance, R_{esp} [A/W] is the photodetector responsivity, and V_π [V] is the half-wave voltage of the electro-optic modulator. There are practical limits to the values of the quantities in the parentheses, so a larger output voltage necessitates amplifying the input in the RF domain, resulting in the aforementioned distortion and fidelity reduction.

In the SALMON modulator by contrast, the bare electro-optic modulator is instead fed by a pump laser which is followed by a cross-phase modulation stage. There, a carrier laser undergoes cross-phase modulation by the modulated pump laser, which imparts the pump laser modulation onto the carrier laser. Finally, the now-modulated carrier laser is photodetected. As a result of this study and using nonlinear optical theory from Agrawal (2007), we have derived that

$$V_{RF,out} = V_{RF,in}\left(2P_{pump}\gamma LK\right)\left(\pi P_{car} R_L R_{esp}/(4V_\pi)\right) \text{ Eq. 2}$$

where P_{pump} [W] is the pump laser power into the cross-phase modulation stage, γ [1/W.m] is the cross-phase modulation stage nonlinear factor, L [m] is the cross-phase modulation stage length, and K [unitless] is a factor near to but less than 1 which depends on the pump and carrier polarizations and propagation loss in the cross-phase modulation stage. We see from Eq. 2 that the gain in output voltage is simply given by the modulation depth enhancement or sensitivity enhancement factor $X \coloneqq 2P_{pump}\gamma LK$. As we shall see below, this quantity can practically be large (X >10), resulting in net gain. In addition, this gain factor is linearly proportional to the pump which shows the ability to increase the modulation depth using purely optical means, with the potential to avoid the use of an RF amplifier and its concomitant degradation of fidelity.

It is important to note that, in commonly used Mach-Zehnder modulators, the input voltage results in a modulator phase, and at the end of the link results in a photodetected voltage. Any increase in the modulator phase results in a larger photodetected voltage. Examining the phase alone allows one to isolate the electro-optic modulator’s properties independent of the rest of the optical link (e.g. photodetector and carrier laser).

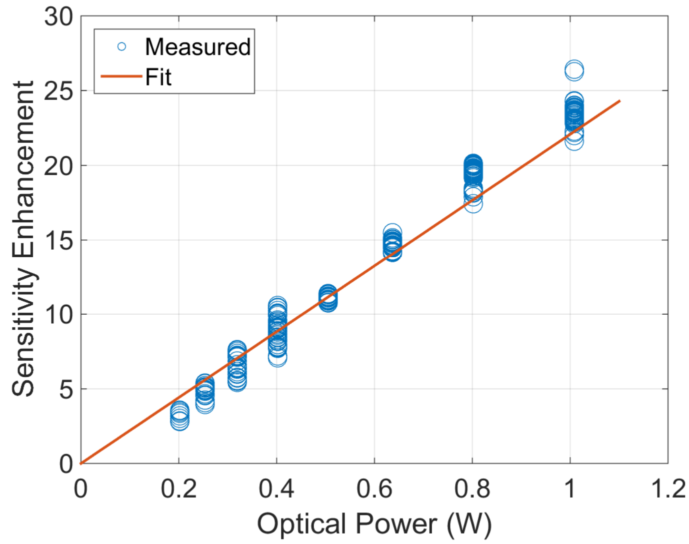

Figure 1. Sensitivity enhancement factor vs. peak optical power into the highly nonlinear fiber. Here, we see the expected linear relationship between the two as predicted by our theory. Fit is sensitivity enhancement factor $X = (22/W)P_{pump}$.

We measured the strength of the sensitivity enhancement factor as a function of optical power (c.f. Figure 1) of this SALMON modulator which uses a highly nonlinear fiber as the cross-phase modulation stage. Sensitivity enhancement was calculated by measuring the modulation depth with and without the cross-phase modulation stage. The model we created predicts a linear relationship between sensitivity enhancement and pump laser power. Our cross-phase modulation stage was a telecommunications wavelength (1.5 μm) highly nonlinear fiber (Sumitomo Electric), a silica optical fiber whose specialty is to strongly confine the optical field to increase the nonlinearity, and as a result has a nonlinear coefficient $\gamma = 30 \times 10^{-3}/W.m$ and length $L = 10^3\ m$. Given the fit in Figure 1 of $X = (22/W)P_{pump}$, this implies $K = 0.37$. The deviation of K from 1 is likely due to a drop in the cross-phase modulation strength from ideality due to walk-off of the relative polarizations of the pump and carrier waves throughout the highly nonlinear fiber, pump loss along the fiber, and pump-carrier group velocity dispersion. Experiment-to-experiment differences in sensitivity enhancement factor could be due to pump and signal polarization drift over time due to environmental fluctuations. The great agreement between theory and experiment lends strong credence to the origin of the observations, and also shows the ability to engineer the amplification strength.

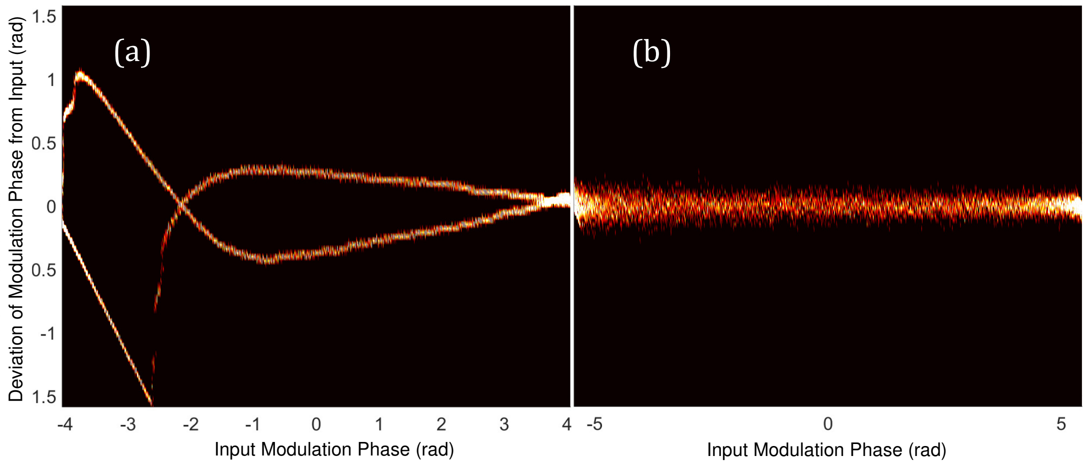

Figure 2. 2D distribution of input modulation phase vs. deviation of modulation phase from input. In these plots, noise manifests as the thickness of the distribution, whereas irreversible distortions scale with area inside hysteresis loops. (a) Using an RF amplifier results in large distortion. (b) Using a cross-phase modulation amplifier results in no visible distortion. Although in this first demonstration using cross-phase modulation exhibits larger noise, the total error is significantly reduced.

We also quantified the noise and distortion introduced by RF amplification and cross-phase modulation, as seen in Figure 2. This figure shows the distribution of amplified modulator phase errors (Deviation of Modulation Phase from Input) as a function of the Input Modulation Phase, so more deviation from no error (a thin, horizontal line at 0) indicates worse performance. In RF-amplified modulator, even use of a high performance RF amplifier (PhotLine, model: DR-AN-20-HO) results in large distortion, as evidenced by the large hysteresis loops (c.f. Figure 2a). In contrast, in the SALMON modulator, no distortion is discernible. In the cases highlighted here, the SALMON modulator is amplifying higher RF frequency (1.5 vs. 0.8 GHz), more RF power (5 dBm vs. -1 dBm), and at a higher sensitivity enhancement factor (25.5 vs. 22.9), than the RF-amplified modulator. One would expect all three of these factors to increase distortion if the cross-phase modulation stage were replaced by an equivalent RF amplifier; however, since we find even less distortion, the SALMON modulator is unequivocally much more linear than the RF-amplified modulator.

We do note, however, the increased noise floor. As this is a first demonstration, more work is needed to determine the source of this noise floor and mitigate it.

Impact on Mission

Many high-speed temporal diagnostics of advanced fusion-class lasers, laser target-chamber dynamics, and weapons tests require detection of weak RF signals that must be sent over long distances to protect valuable hardware from damage. A new electro-optic modulator technology for delivery of these signals will enable both high sensitivity and fidelity in support of the Laboratory's core competencies in lasers and optical materials science and technology and high-energy-density science. As a result of this work, the laboratory has gained a unique modulator technology for high fidelity capture of weak signals. In addition, this addresses a pressing need for DARPA: higher sensitivity for RADAR applications. Electronic warfare requires the best performance possible. However, weak signals are often lost in a sea of noise, and jamming signals and their distortions. The SALMON modulator has the potential to provide the increase in sensitivity necessary for these applications. Finally, the funding from this effort helped provide support necessary to hire David Perlmutter, a new permanent staff member with expertise in digital signal processing.

Conclusion

As a result of this LDRD, we found that the SALMON modulator has passed the test of feasibility, that is, it exhibited sensitivity enhancement greater than 10 (actually found >20) and significantly lower distortions than a state-of-the-art RF amplifier. These results are very promising for the future deployment of this class of modulators in an array of applications. However, this study also raised a question about its noise performance. Although the SALMON modulator clearly outperformed a high performance RF-amplified modulator, there is potential to significantly improve its performance. In particular, further work is needed to ascertain the source of the additional noise in the SALMON modulator in order to determine whether it can be mitigated. In addition, there is a very large and rich parameter space to explore to further optimize the performance of SALMON modulators, including but not limited to choice of optical wavelength and highly nonlinear fiber (which influences nonlinearity and dispersion).

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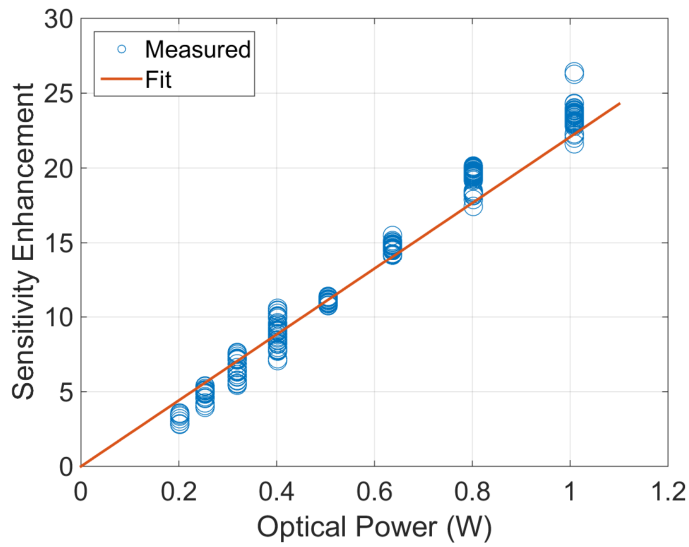

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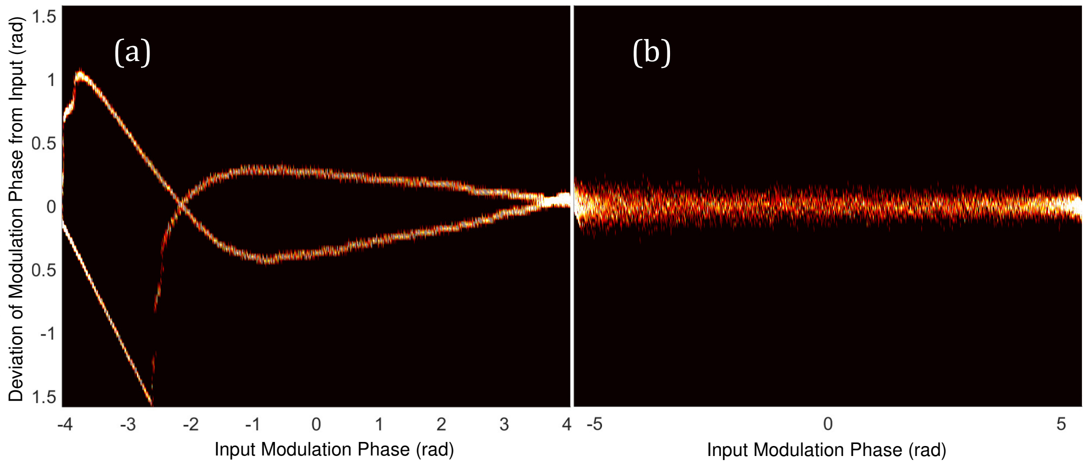

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